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**14. ABSTRACT**
This report summarizes our five year project to study coherent beam combining using an array of passively coupled fiber lasers. Our approach is a novel one, based on a dynamical description of the fundamental physical processes involved. Our primary objective was to develop a fundamental, quantitative understanding of coherent beam combining in fiber laser arrays. This understanding could then be used to explore the potential scalability of the observed coherence to very large arrays, and to investigate novel schemes and architectures aimed at mitigating

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| UU | UU | UU | UU | | Kurt Wiesenfeld |
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## Report Title

A Dynamical Approach to High Power Fiber Laser Arrays: Final Report

## ABSTRACT

This report summarizes our five year project to study coherent beam combining using an array of passively coupled fiber lasers. Our approach is a novel one, based on a dynamical description of the fundamental physical processes involved. Our primary objective was to develop a fundamental, quantitative understanding of coherent beam combining in fiber laser arrays. This understanding could then be used to explore the potential scalability of the observed coherence to very large arrays, and to investigate novel schemes and architectures aimed at mitigating difficulties encountered by conventional array architectures.

The project involved both theoretical and experimental components. On the theory side, the main accomplishment was the development of a quantitatively predictive dynamical model consisting of coupled iterative maps. This was an entirely novel approach to this field, and its success has already stimulated other researchers to take a similar approach. The experimental effort was essential in enabling us to fine tune the theory, and extend the theory to account for longitudinal mode competition which is the fundamental mechanism behind the spontaneous coherent beam combining observed in these systems. We also explored (for the first time in these systems) detailed time-resolved dynamics of the modal spectra during the evolution to coherence.

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## List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

### (a) Papers published in peer-reviewed journals (N/A for none)

K. Wiesenfeld, S. Peles, J. Rogers, "Effect of gain-dependent phase shift on fiber laser synchronization," IEEE J. Selected Topics Quantum Electronics 15, 312-319 (2009).

W. Ray, J. Rogers, K. Wiesenfeld, "Coherence between two coupled lasers from a dynamics perspective," Optics Express 17, 9357-9368 (2009).

**Number of Papers published in peer-reviewed journals:** 2.00

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### (b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

**Number of Papers published in non peer-reviewed journals:** 0.00

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### (c) Presentations

**Number of Presentations:** 0.00

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### Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

W. Ray, Y. Matsuoka, J. Rogers, K. Wiesenfeld, " Patterned disorder in a fiber laser array improves coherence," SSDLTR 2009 Technical Digest, 153-157 (2009).

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):** 1

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### Peer-Reviewed Conference Proceeding publications (other than abstracts):

**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):** 0

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### (d) Manuscripts

W. Ray, Y. Matsuoka, and K. Wiesenfeld, "Experimental control of polarization sensitivity in a fiber laser array", submitted to Optics Express.

K. Wiesenfeld, Y. Matsuoka, W. Ray, "Origin of the self-pulsing instability in fiber lasers", submitted to Physical Review E.

**Number of Manuscripts:** 2.00

## Patents Submitted

## Patents Awarded

## Awards

"Sustained Research Award" to Kurt Wiesenfeld (2010). This is awarded each year to a Georgia Tech faculty member by the GT chapter of Sigma Xi.

## Graduate Students

| NAME | PERCENT_SUPPORTED |
|---|---|
| Yamato Matsuoka | 1.00 |
| Tetsuya Ishikawa | 0.50 |
| Alex Lesov | 0.50 |
| **FTE Equivalent:** | **2.00** |
| **Total Number:** | **3** |

## Names of Post Doctorates

| NAME | PERCENT_SUPPORTED |
|---|---|
| Will Ray | 1.00 |
| **FTE Equivalent:** | **1.00** |
| **Total Number:** | **1** |

## Names of Faculty Supported

| NAME | PERCENT_SUPPORTED | National Academy Member |
|---|---|---|
| Kurt Wiesenfeld | 0.25 | No |
| **FTE Equivalent:** | **0.25** | |
| **Total Number:** | **1** | |

## Names of Under Graduate students supported

| NAME | PERCENT_SUPPORTED |
|---|---|
| **FTE Equivalent:** | |
| **Total Number:** | |

**Student Metrics**

This section only applies to graduating undergraduates supported by this agreement in this reporting period

| | |
|---|---|
| The number of undergraduates funded by this agreement who graduated during this period: ...... | 0.00 |
| The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... | 0.00 |
| The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... | 0.00 |
| Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): ...... | 0.00 |
| Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering: ...... | 0.00 |
| The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ...... | 0.00 |
| The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ...... | 0.00 |

## Names of Personnel receiving masters degrees

NAME

**Total Number:**

## Names of personnel receiving PHDs

NAME

**Total Number:**

## Names of other research staff

| NAME | PERCENT_SUPPORTED |
|---|---|

**FTE Equivalent:**

**Total Number:**

## Sub Contractors (DD882)

## Inventions (DD882)

## Scientific Progress

see attached document

## Technology Transfer

# A Dynamical Approach to High Power Fiber Laser Arrays

Final Report

Grant Number W911NF-05-1-0506

Covering Period 01-OCT-2005 through 30-SEP-2010

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# Contents

## Introduction

We performed theoretical and experimental investigations of nonlinear self-organization of fiber beam combining. The time course of the project divided into two phases. Our central goal (and accomplishment) during the first, two-year phase was to develop, test, and refine a dynamical model of the fundamental physics of fiber laser arrays. Having established that the theoretical model correctly reproduces a wide variety of experimental findings, we entered into the project's second phase, in which we established our own laboratory with several novel capabilities for exploring the fundamental dynamics of coherent beam combining in passively coupled fiber laser arrays. These experiments, together with our continued development of the theoretical model, afforded us new insights into the processes governing the self-organization of the beam energy leading to coherent combining.

# PHASE ONE FINDINGS

### *Single Element Dynamics and Small Array Coherence*

The central thrust of the project's first phase (2005-2007) was to check our new dynamical model against existing experimental data. The data available to us consisted of papers previously published in the technical literature, and unpublished data from HRL Laboratories. By the end of this phase, we were able to achieve excellent agreement between model and experiments on single fibers and systems of two coupled fibers. These findings are reported in references [1] and [2]. Among the things captured by the model are (i) the onset of major dynamical transitions, (ii) the effects of noise in shifting the Hopf point and lowering the pulse amplitude, (iii) the timing and amplitude decay of transient pulses during relaxation to the CW state, (iv) the effect of differential reflectivity on the coherent output of coupled fiber lasers, and (v) the fundamental difference in CW instability (and pulsing) in high loss vs. low loss fibers.

One of the major outcomes of this phase of the project was the determination that the atomic gain is a crucial dynamical variable, every bit as important as the electric field in determining the eventual behavior of the fiber laser array. In particular, it is essential to distinguish between 3- and 4-level fiber lasers. A key refinement of our model was to properly account for this difference [1].

### *Symmetry, Symmetry Breaking, and Coherent Combining*

From further analysis of the theoretical model, we made some interesting and rather unintuitive discoveries. Chief among these is the role of uniformity and symmetry in suppressing robust coherence. By considering particular geometries for relatively small arrays (up to seven fibers arranged in a bundle), we concluded that breaking (i.e. lowering) system wide uniformity can greatly enhance the output coherence. This conclusion is consistent with previously published fiber laser array experiments which reported that the experimentally observed coherent output may have required as an essential ingredient a certain degree of disorder [3].

### *The Role of Gain-Dependent Phase Effects*

Early experiments reporting synchronization of fiber laser arrays at low and moderate pump levels also found a systematic degradation of coherence at high pump levels. A possible explanation for this degradation is that the key dynamical interaction becomes saturated at high pump levels. It had been suggested [4] that this key interaction is the phase shift due to gain-dependent refractive index within each fiber. We explored this hypothesis by modifying our dynamical model to account for this effect. Our key finding is that while its presence can enhance inphase stability, this mechanism is not the essential one responsible for the generation of coherence. From a fundamental perspective, then, this feature can be ignored; on the other hand, including it can improve the quantitative correspondence between theory and experiment. Our analysis and findings were published in reference [5].

# PHASE TWO FINDINGS

## Further Development of the Theoretical Model

In this second phase of the project we turned our theoretical focus toward understanding the role of the very large number of active longitudinal modes present in each fiber laser. All previous efforts had assumed single mode operation. Although the single-mode model could explain a wide variety of experimentally observed behaviors, it was fundamentally incapable of explaining the modal selection that spontaneously occurred in the array. We extended the dynamical model to take account of the large number (tens of thousands) of longitudinal modes capable of lasing. This represents a jump in both the complexity of the model and its physical fidelity.

Simulations revealed that the array settles down very quickly to a dynamical state in which only a small number of modes contain almost all of the available energy. Thus, the parameter tuning needed in the single-mode model is found to be unnecessary; rather, the coherent combining observed in experiments is the result of dynamical selection among competing (coupled) longitudinal modes.

We also used the multimode model to revisit the idea of weak-link synchronization, in which unequal pumping of a subset of the lasers in an array can lead to improved coherence in the output, as compared with an all-pumped scheme. This improvement is expected to be greatest when the individual elements are not carefully matched, which is especially relevant for realistic arrays operated under rugged conditions [6].

## Experimental Design and Diagnostic Capabilities

The experimental thrust during the project's phase two was geared towards obtaining measurements to reveal the dynamical mechanisms behind coherent combining. The primary focus was resolving the dynamics of the array's optical spectrum in both frequency and time. For years the longitudinal mode dynamics have been assumed to be responsible on the one hand for the robust coherence of small arrays, and on the other for the ultimate breakdown of coherence for large arrays (i.e. more than eight elements). We concentrated on the most commonly utilized passive arrays, but also investigated coherence in a more complex implementation. Additionally, we studied the role of polarization control, since its necessity remains controversial in the literature and it is an important consideration in practical realizations.

To understand the success of passive arrays with a few elements and the coherence degradation with increasing array size, we constructed fiber laser arrays containing two to eight elements using Nd-doped and Yb-doped gain media. In both cases the power of individual elements was limited to ~100 mW so that the Kerr effect and other high power instabilities did not interfere with the coherence. The passive architecture utilized involved a beam-combining architecture designed to funnel the light generated by array members to a single output port. Coupling was achieved using a nested series of 2x2 interferometric fiber couplers and loss-discrimination was achieved by adding a reflector only to the output port where emission was desired. A schematic of this passive array design is shown in Fig. 1.

Our experiments employed novel diagnostics, providing simultaneous measurements of the intensity and optical spectrum dynamics at fine resolution of both time and the emission frequency. While previous efforts had examined static pictures of the longitudinal mode spectrum or average intensities over seconds or minutes, we were able to resolve the simultaneous time evolution of the intensity and optical spectrum on a time scale as fast as 3 ms. The optical spectrum was resolved using an optical heterodyne technique to 1 MHz allowing identification of individual longitudinal modes.

## Observation of Longitudinal Mode Competition in Large Arrays

We measured the performance degradation of Yb-doped fiber laser arrays as their size was increased one laser at a time up to eight elements. Figure 2 (a) plots the reduction in the average beam-combined intensity (red circles) as array size was increased. The total intensity from all output ports was also recorded and the average values are represented by the blue line. The reduction of total output from the port with the reflector is consistent with observations of other research groups utilizing this passive array. The plot in Fig. 2 (b) shows that the array efficiency, defined as the fraction of light emanating from the desired output port, begins to fall sharply as the array size grows beyond five elements.

This degradation with array size is understood as a limitation of the array to find a suitable frequency in the operational bandwidth that can pass through the mismatched fiber lengths and reenter the coupler with aligned phases. If a frequency is not available that has the desired alignment of phases, the array emits at a sub-optimal frequency causing a consequential deterioration in performance.

To test this interpretation, we statistically looked at the number of longitudinal modes exhibited by the system at various array sizes. Distributions of the number of longitudinal modes appearing in a 20 ms time frame were constructed from 500 successive frequency scans. Figure 3 (a) shows that an array of two elements almost always emits at 10-20 longitudinal modes. Many longitudinal modes are able to propagate through the mismatched gain arms and retain near-perfect coherence upon entry to the coupler. A similar phenomenon is seen in the mode count distribution of a four-laser array in Fig. 3 (b) although the average number of exhibited modes decreases to six. Again near-perfect coherence is maintained in this system. However, only one or a few modes are found when the array size is increased to eight elements, as evidenced in Fig. 3 (c). Clearly the mode competition is stiffer and most of the time an optimal mode cannot be found. The small number of exhibited modes is evidence of the large difference between the characteristic phase alignment of frequencies in the spectral bandwidth.

A similar phenomenon was observed in passive arrays of up to six elements constructed using Nd-doped lasers and a wider operational bandwidth. Individual scans of the optical spectrum in Fig. 4 show that energy is concentrated in fewer modes as the array size is increased. This decline is further evidenced in Fig. 5 showing the statistics of the number of modes exhibited in this system.

## Direct Evidence of Mode Competition in 8-laser Arrays

We also examined how the longitudinal mode spectrum changes in time, particularly in relation to interruptions of the array coherence. Indeed, in a noise-stabilized environment we were able to observe slow fluctuations in the coherence of Yb-doped laser arrays. The plot in Fig. 6 (a) shows the evolution of the beam-combined intensity in an 8-laser array in a 10 s interval. Substantial dips in the intensity by a third of the total value are evidenced.

The longitudinal spectrum was simultaneously scanned at intervals of 0.02 s and a logarithmic entropy measure of the number of exhibited modes was calculated. The time series of this measure is shown in Fig. 6 (b). The interesting feature of the output is that only one or two modes are exhibited when the intensity slowly goes through a maximum. Sharp increases are observed when the intensity recovers from a dip. These results may be interpreted as follows: near an intensity peak the array settles on a longitudinal mode or two, but as fiber lengths drift the coherence worsens. The system will hold on to these modes (as evidenced by (not shown) spectral plots like Fig. 4) until other longitudinal modes are able to compete. A quick competition is conducted and the system settles on a distinct set of longitudinal modes until the process is again repeated. This provides the clearest and most direct evidence of longitudinal mode competition in passive arrays.

## Measurement of Array's Ability to Maintain Coherence

We performed a more controlled set of measurements designed to quantitatively assess the time scales involved in the dynamical adjustment of a passive array to fiber length fluctuations. We set up a two laser array and in one gain arm attached a piezo-electric actuator that could be modulated to effectively stretch the fiber length by one full wavelength. Without modulation the system exhibited high coherence. Figure 7 plots the coherence measured when the actuator was driven with a sinusoidal voltage at increasing frequencies. The performance was seen to steadily but gracefully degrade when low frequency modulation was applied. However, once the modulation exceeded 5 kHz, the coherence almost instantly vanished. These results establish a time scale limitation to the array's capability to track changes in fiber lengths due to environmental perturbations.

## Loss Discrimination in Arrays with Patterned Pumping

The previous experiments focused on studying the dynamics associated with the most commonly utilized class of passive array architectures. In short, these designs filter out all light except for frequencies with a desired phase alignment. However, high coherence has been experimentally observed in other passive arrays where the symmetry of the system is broken but no clear loss-discrimination mechanism is apparent. Our own theoretical investigations into an alternative class of arrays predict similar coherence enhancement under non-uniform operation of elements.

We performed thorough experiments on an alternative passive array design with three Yb-doped fiber lasers. A schematic of the experiment is shown in Fig. 8. The three lasers are coupled asymmetrically by interferometric fiber couplers and each laser's output contains a reflector (unlike the standard beam-combining architecture where only one reflector is attached). When the array is operated uniformly, that is, each laser is pumped identically and each suffers nearly equal losses, then the output array coherence is extremely poor. The coherence is gauged by measuring the visibility of the fringes generated by the array output in the far-field.

The array coherence was greatly improved when the pump and cavity losses of the middle laser were detuned away from the outer laser elements. Moderate increases in coherence were observed when the pump of the middle laser element was driven above or below the level of the outer lasers. A significant improvement in far-field output was observed when the middle laser pump detuning was repeated and heavy cavity losses were additionally applied near the output port of the middle laser.

Figure 9 shows the average array coherence measured at various pump settings of the middle laser when additional losses were applied near the middle laser output. The outer laser elements are fixed at 10% above threshold. We observe that the lowest coherence is measured when the pump of all three lasers is the same. A nearly five-fold increase in array coherence is measured when the middle laser is pumped below its lasing threshold. The enhancement can be physically traced to a loss-discrimination mechanism occurring at the interface of the two directional couplers. Specifically, under non-uniform driving and losses, the array operates at frequencies that minimize the light sent to the gain or output arm of the middle laser since it is more inefficient than the outer two. This effectively reduces the modal expression and surviving frequencies generate a higher coherence in the far-field.

Detailed simulations of this system using our dynamical model successfully capture the coherence enhancement seen in the above experiments. The model predicts coherence enhancement when the middle laser pump is detuned with and without additional losses. Like the experiment, the coherence gains are larger when additional losses are present. Further analysis of the model suggests that the coherence enhancement results from a combination of longitudinal mode discrimination and a stabilization of the intensity dynamics occurring within the exposure time of the camera that measures the far-field. This behavior has connections to a patterned pumping phenomenon called 'weak-link synchronization' that was first studied by our research group.

## The Role of Active Polarization Control

Finally, we performed experiments and analysis to determine the necessity of actively controlling the polarization state in the individual array members of passive arrays. A proper alignment of polarizations in the coupling region is important to achieve efficient interferometric combining. A motivation for the study of this practical issue is the conflicting reports that exist in the literature about the need to manually adjust the polarizations to achieve high coherence. Once adjusted, fiber polarization tends to be stable for relatively long time periods on the order of hours or days. Nevertheless, resolution of this issue is important for the design of large arrays and complex cavity designs requiring multiple polarization controllers for each element.

We investigated the necessity of polarization control to achieve efficient coherent beam-combination in a two-laser fiber array using Yb-doped lasers. A schematic of the experimental setup is shown in Fig. 10. Here polarization controllers are placed in each of the laser gain arms as well as in the common output port. To test the robustness of the array coherence to polarization fluctuations, we adjusted the polarization of one of the gain arms while keeping the other two arms fixed. The results in Fig. 11 (a) represent a typical outcome of this experiment. Clearly the coherence of the array, assessed by the fraction $\varepsilon$ of the total light appearing in the beam-combined output port, varies significantly with polarization adjustments. This lends credence to other observations that array coherence is sensitive to manual polarization alignment.

However, when this experiment was repeated after adjusting the polarization state of the other gain arm by a fixed amount (and leaving it fixed), the coherence swings are not as sensitive. This is evidenced in Fig. 11 (b). Indeed, at another setting of the other gain arm the sensitivity vanishes completely. Therefore, active adjustment of the polarization state can be determined to be both necessary and unnecessary in the same system. This result solves the paradox presented in the literature.

The fixed setting of the polarization state corresponding to insensitivity of array coherence by manipulations of the other gain arm is intriguing from a system design standpoint. We next looked at the prevalence of such settings. The plot in Fig. 12 shows that the minimum array coherence achieved when the fixed polarization state of one gain arm is detuned from its insensitive point. We conclude that this setting is indeed an isolated point in the parameter space of the polarization controller. Generally, active polarization control will be necessary in this type of system unless the remaining gain arms are finely tuned to a particular operating point.

## References


1. "Refined fiber laser model," W. Ray, K. Wiesenfeld and J.L. Rogers, Phys. Rev. E 78, 046203 (2008).

2. "Coherence between two coupled lasers from a dynamics perspective," W. Ray, K. Wiesenfeld, and J. Rogers, Optics Express 17, 9357-9368 (2009).

3. H. Brusselbach et al, Optics Letters 30, 1339 (2005).

4. H. Brusselbach et al, J. Opt. Soc. Am. B 22, 347-353 (2005).

5. "Effect of gain-dependent phase shift on fiber laser synchronization," K. Wiesenfeld, S. Peles, and J.L. Rogers, IEEE J. Selected Topics in Quantum Electronics 15, 312 – 319 (2009).

6. "Weak-link synchronization", D. Tsygankov and K. Wiesenfeld, Phys. Rev. E 73(2), 26222/1-6 (2006).

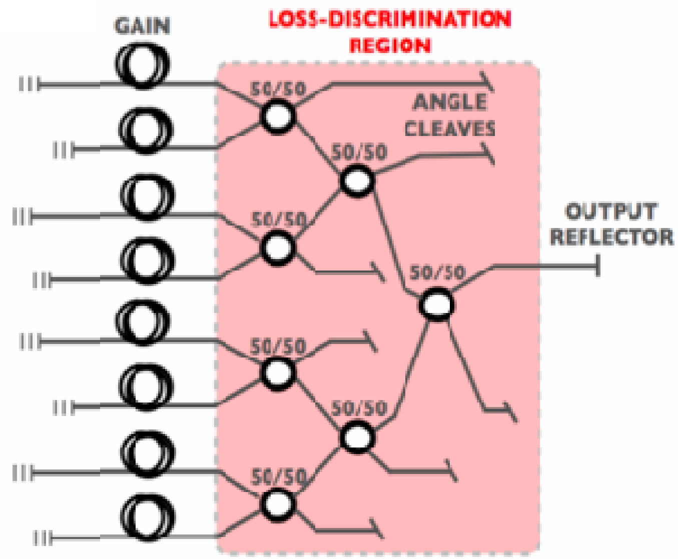


**Fig. 1: Schematic of a fiber laser array of eight elements in a passive coupling architecture. This array architecture emits at wavelengths that most efficiently combines the array light to the sole output port with a reflector.**

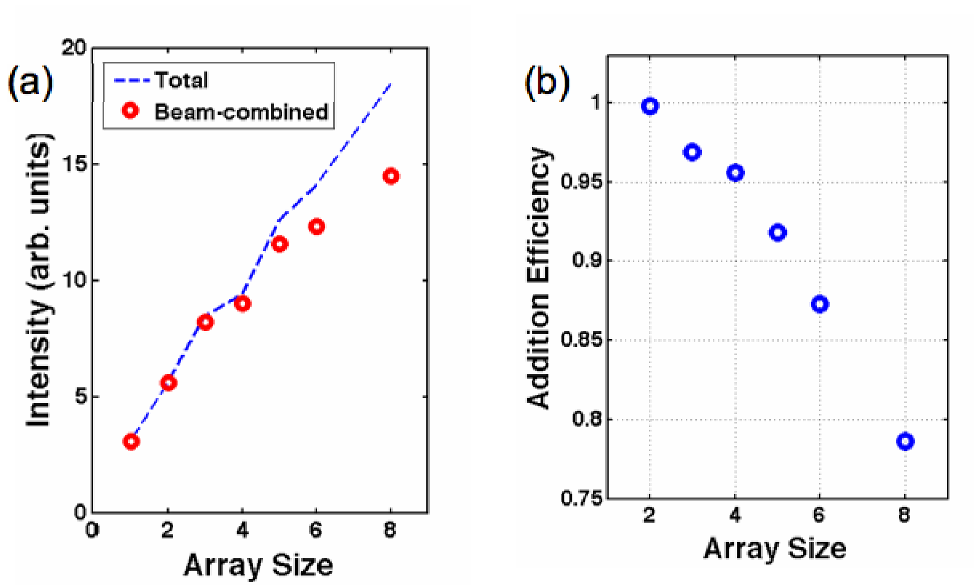


**Fig. 2: (a) The intensity measured from the output port with the reflector (red circles) and the total intensity including angle-cleaved ports (blue line) in Yb-doped fiber laser arrays at various array sizes using the beam-combining passive architecture shown in Fig. 1. (b) The addition efficiency of the arrays in (a). Addition efficiency is the fraction of total light emitted from the output port with a reflector.**

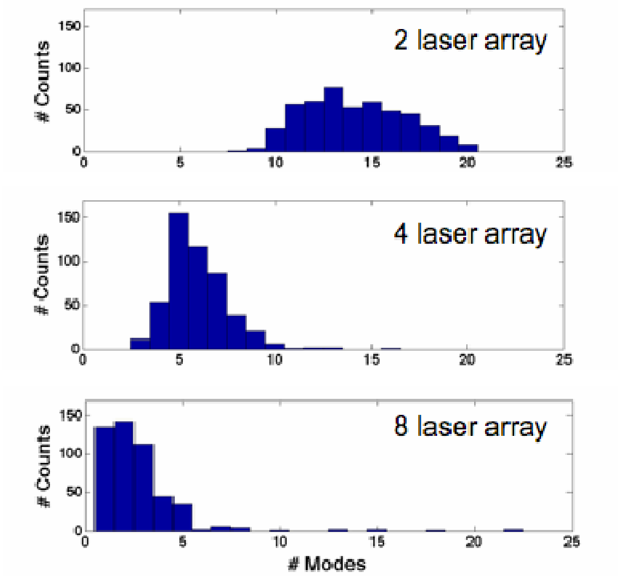


**Fig. 3: The distribution of the number of modes exhibited in successive scans of the optical spectrum of Yb-doped lasers in the beam-combining architecture in Fig. 1 for various array sizes.**

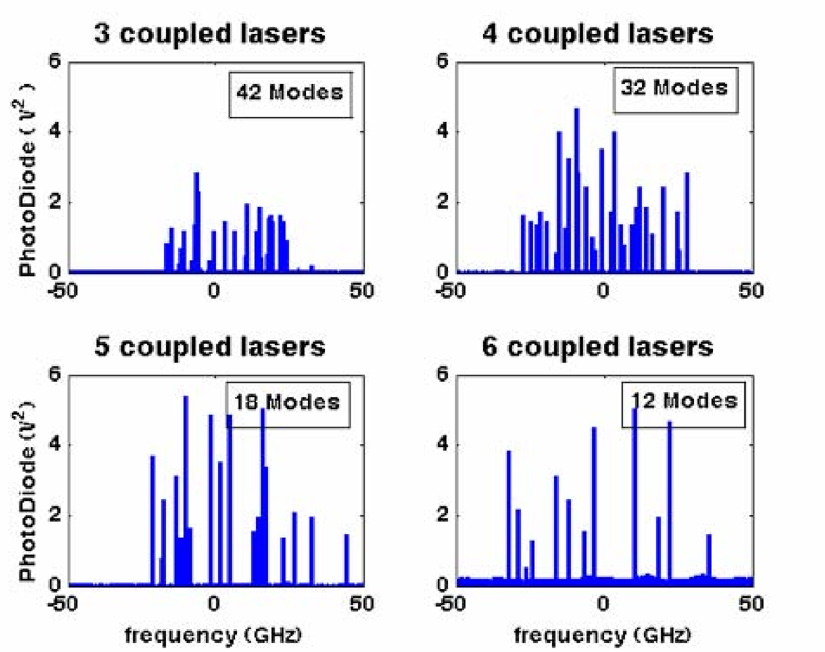


**Fig. 4: Resolved snapshots of the longitudinal modes emitted in the operational bandwidth of Nd-doped fiber lasers in the beam-combining architecture shown in Fig. 1 at various array sizes. Energy of the array is concentrated in fewer longitudinal modes as array size is increased due to increased constraints of the loss-discriminator.**

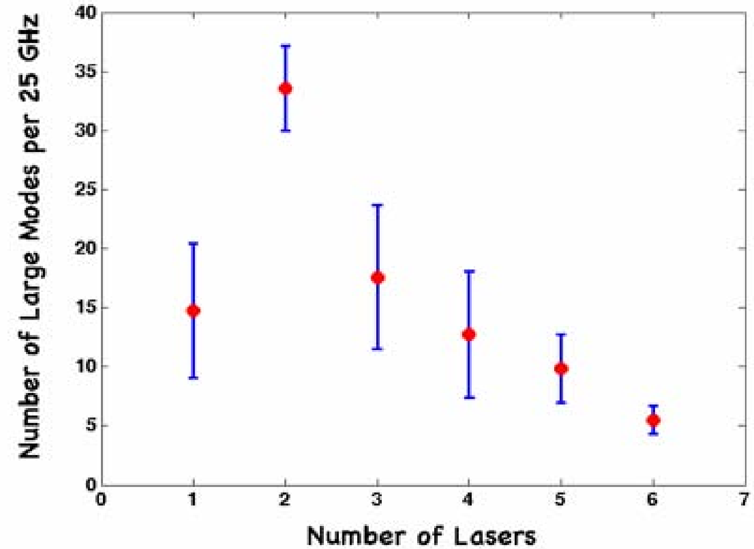


**Fig. 5: The average number of modes (and standard deviations) recorded in scans of the optical spectrum of Nd-doped lasers in the beam-combining architecture in Fig. 1 for various array sizes.**

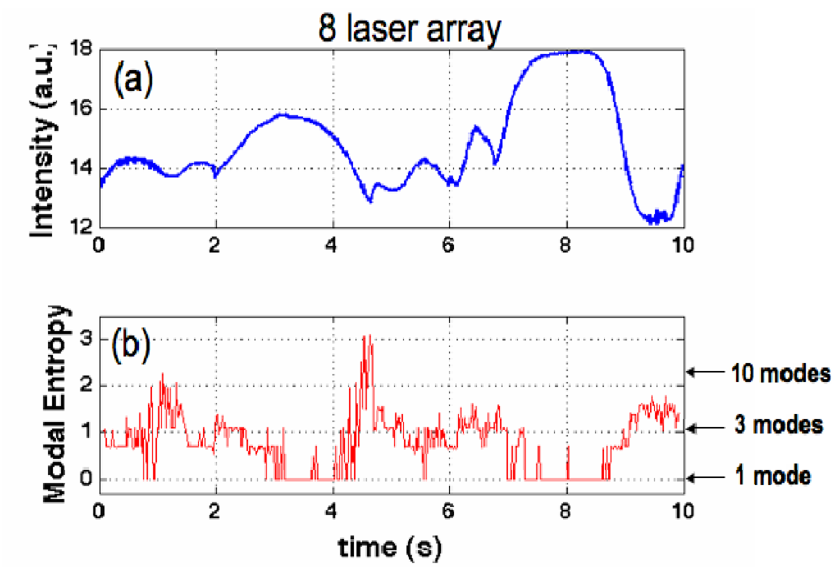


**Fig. 6: (a) The slowly-varying intensity dynamics recorded from the output port with the reflector in an eight laser passive array. (b) The modal entropy calculated from scans of the optical spectrum that were recorded simultaneously with the intensity in (a). The modal entropy indicates the number of modes exhibited during a scan. Peaks in the entropy coincide with decreases in the intensity, an indication that when fiber lengths drift the array 'searches' for a new emission spectrum that improves array coherence.**

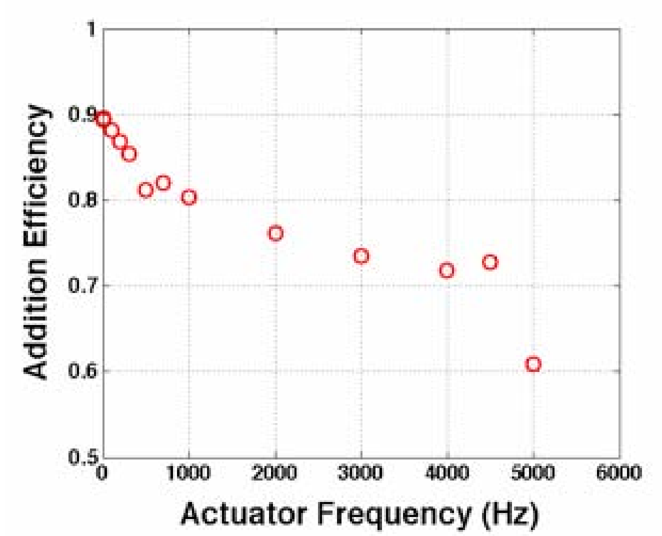


**Fig. 7: Deterioration of the coherent-combining efficiency in a two-laser array as the path length of one laser is sinusoidally stretched at the indicated frequency by an actuator (over the distance of a wavelength). The graceful degradation shows that the system reasonably tracks the modulated fiber length (by adjusting the emission spectrum) up to 4.5 kHz.**

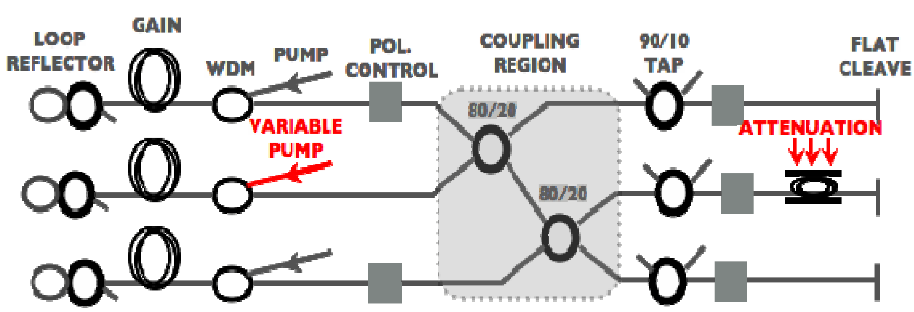


**Fig. 8: Schematic of a three laser array with patterned pumping and loss. Lowering the middle laser's pump below threshold and applying losses to the output results in high coherence in the far-field array emission.**

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

**Fig. 9: Fringe visibility measured in the far-field of the three laser array shown in Fig. 8 as the pump of the middle laser is detuned from the operating point of the outer two lasers. The outer two lasers are fixed at 10% above threshold. Heavy losses are additionally applied in the middle laser output port. The coherence of the array is observed to improve as the pump of the middle laser is tuned above and below the symmetrical operating point.**

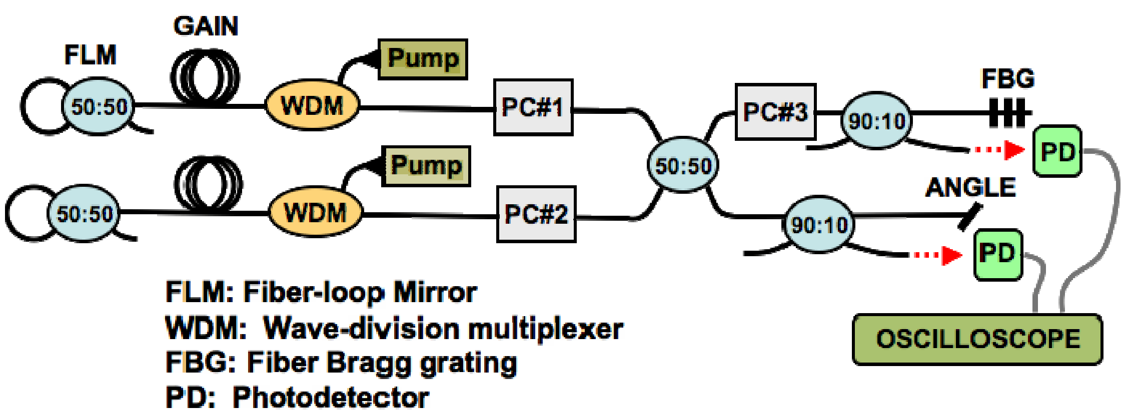


**Fig. 10: Schematic of the two laser passive array used to study the impact of active polarization control on coherent combining efficiency.**

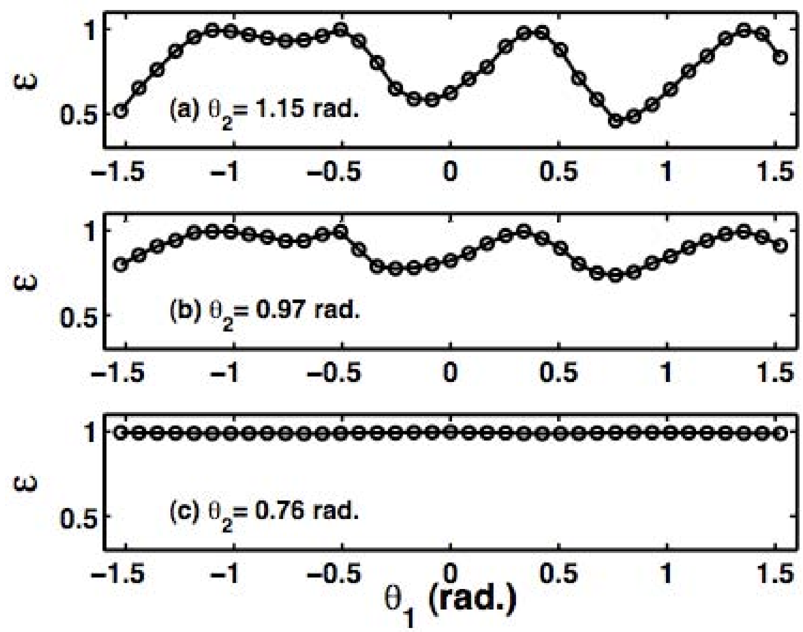


**Fig. 11: Coherent-combining efficiency ε measured when the orientation of the light entering the polarization controller #1 is tuned for (a)-(c) three fixed orientations of polarization controller #2. The sensitivity of the combining efficiency to manipulations of polarization controller #1 depends on the setting of the other controllers.**

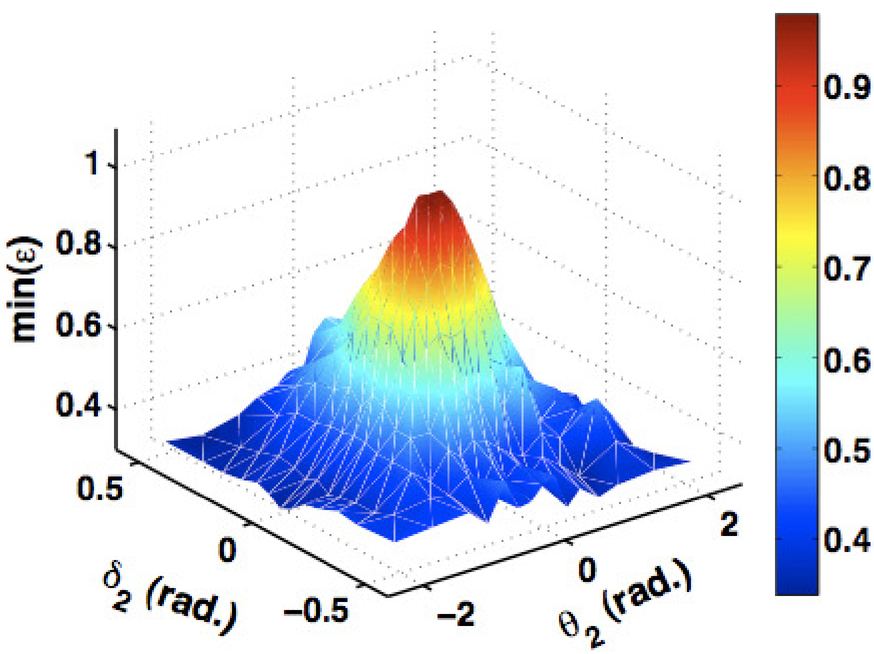


**Fig. 12: The minimum coherent-combining efficiency ε measured for variations of polarization controller #1 while the settings of polarization controller #2 are fixed. The fixed values of polarization controller #2 are plotted relative to the setting corresponding to the least sensitivity (highest min(ε)).**